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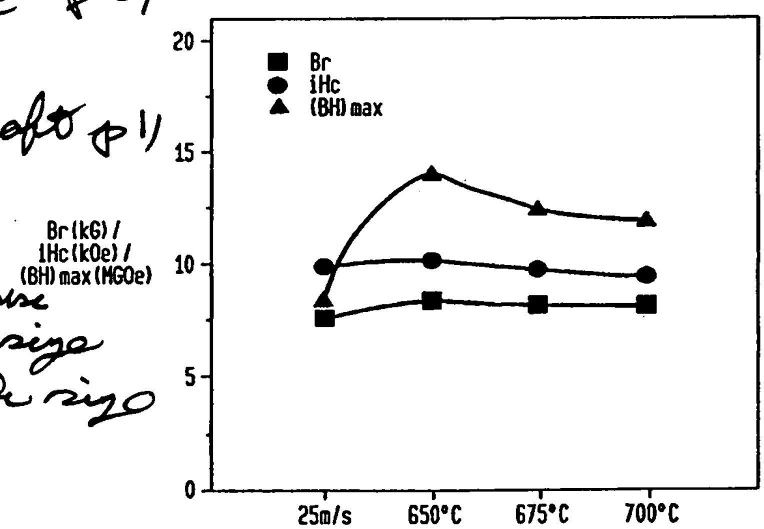

(57) Abstract

Magnetic nanocomposite materials including iron, rare earth elements, boron, refractory metals and cobalt which have favorable magnetic properties and are suitable for making bonded magnets are disclosed. Compositions of the present invention can be of the formula: $(Nd_{1-y}La_y)_vFe_{100-v-w-x-z}Co_wM_zB_x$, where M is at least one refractory metal selected from Ti, Zr, Hf, V, Nb, Ta, Cr, Mo and W; v is from about 5 to about 15; w is greater than or equal to 5; x is from about 9 to about 30; y is from about 0.05 to about 0.5; and z is from about 0.1 to about 5. Preferably M is at least Cr. These materials have good magnetic properties and are suitable for use in preparing bonded magnets.

Bx 9-30
Rv 5-15

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HIGH PERFORMANCE IRON-RARE EARTH-BORON-REFRACTORY-COBALT NANOCOMPOSITES

FIELD OF THE INVENTION

The present invention relates to magnetic materials, and more particularly relates to magnetic nanocomposite materials including iron, rare earth elements, boron, refractory metals and cobalt which have favorable magnetic properties and are suitable for making bonded magnets.

BACKGROUND INFORMATION

Magnetic alloys containing neodymium, iron and boron have been widely studied for use in sintered and bonded magnets due to their favorable magnetic properties. The $Nd_2Fe_{14}B$ phase has been identified as a hard magnetic phase exhibiting particularly good magnetic properties.

U.S. Patent Nos. 4,402,770, 4,409,043 and Re. 34,322 to Koon, which are incorporated herein by reference, disclose magnetic alloys comprising lanthanum and other rare earth elements, transition metals such as iron and cobalt, and boron within specified ranges. Although the disclosed alloys have been found to possess good magnetic properties, such alloys do not have optimal properties, and have not become commercially viable.

The present invention provides favorable magnetic properties and are suitable for commercial production of bonded magnets.

SUMMARY OF THE INVENTION

The present invention provides a nanocomposite magnetic material of controlled composition which exhibits improved magnetic properties and can be easily processed. An object of the present invention is to provide a nanocomposite magnetic material comprising Fe, rare earth elements (preferably La, Pr and Nd), B, refractory metals and Co within specified ranges.

Compositions of the present invention can be of the formula: $(Nd_{1-y}La_y)_vFe_{100-v-w-x-z}Co_wM_zB_x$, where M is at least one refractory metal selected from Ti, Zr, Hf, V, Nb, Ta, Cr, Mo and W; v is from about 5 to about 15; w is greater than or equal to 5; x is from about 9 to about 30; y is from about 0.05 to about 0.5; and z is from about 0.1 to about 5. Preferably, M is Cr.

A further object of the present invention is to provide a nanocomposite magnetic material including a hard magnetic phase, a soft magnetic phase, and, preferably a refractory metal boride precipitated phase. The hard magnetic phase is preferably $Nd_2Fe_{14}B$, while the soft magnetic phase preferably comprises α-Fe, Fe_3B or a combination thereof. Most preferably, the material comprises the α-(Fe,Co) and $R_2(Fe, Co)_{14}B$ phases.

The present invention provides a method of making a nanocomposite magnetic material. The method includes the steps of providing a molten composition comprising Fe, rare earth elements (preferably Nd and La), B, at least one refractory metal (preferably Cr), and Co, rapidly solidifying the composition to form a substantially amorphous material, and thermally treating the material.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1: The magnetic performance of the $(Nd_{0.95}La_{0.05})_{9.5}Fe_{78}Cr_2B_{10.5}$ ribbons in the as-spun state (Vs=25 m/s) and after optimum heat treatment. Fig. 2: X-ray diffraction pattern of $(Nd_{0.95}La_{0.05})_{9.5}Fe_{78}Cr_2B_{10.5}$ ribbon melt quenched at Vs=25 m/s. Fig. 3: The magnetic properties of the $(Nd_{0.95}La_{0.05})_{9.5}Fe_{78-x}Co_xCr_2B_{10.5}$ (x=0-10) ribbons after optimum heat treatment. Fig. 4: The demagnetization curves of the $(Nd_{0.95}La_{0.05})_{9.5}Fe_{78-x}Co_xCr_2B_{10.5}$ (x=0-10) ribbons after optimum treatment. Fig. 5: TMA scans of the thermally treated $(Nd_{0.95}La_{0.05})_{9.5}Fe_{78-x}Co_xCr_2B_{10.5}$ (x=0-10) (a) x = 0 (b) x = 2.5 (c)x = 5 (d) x = 7.5 and (e) x=10 showing the existence of two magnetic phases, i. e. 2:14:1 and α-Fe, and the increase of Tc in both phases. Fig. 6: X-ray diffraction patterns of the $(Nd_{0.95}La_{0.05})_{9.5}Fe_{78-x}Co_xCr_2B_{10.5}$ ribbons after optimum heat treatment, where (a) x = 0, (b) x = 2.5, (c)x = 5, (d) x = 7.5, and (e) x=10. Fig. 7: TEM microstructures of $(Nd_{0.95}La_{0.05})_{9.5}Fe_{78-x}Co_xCr_2B_{10.5}$ ribbons with optimum magnetic properties, where (a) x=0, (b) x=5, and (c) x=10. Fig. 8: The variation

of δM with the externally applied magnetic field for alloy ribbons of $(Nd_{0.95}La_{0.05})_{9.5}Fe_{78-x}Co_xCr_2B_{10.5}$ (x=0-10).

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Because of their potential high remanence (B_r) and maximum energy product ($(BH)_{max}$), nanocomposites have been intensively studied for bonded magnets. In the NdFeB system, two types of nanocomposite magnets, namely, α-Fe/$Nd_2Fe_{14}B$ [1] and Fe_3B /$Nd_2Fe_{14}B$ [2,3], have been developed. The B_r of these nanocomposites can be strongly influenced by the chemical composition as well as the average grain size of individual phases, volume fraction and distribution of α-Fe and $Nd_2Fe_{14}B$[1] or Fe_3B and $Nd_2Fe_{14}B$ [2,3]. Moreover, the B_r and $(BH)_{max}$ can be further improved by increasing the saturation magnetization of the soft magnetic phase (α-Fe) and/or the hard magnetic phase (the 2:14:1 phase). Similarly, the intrinsic coercivity, ${}_iH_c$, and squareness are strongly affected by elemental substitutions and the microstructure [4,5,6]. Conventional NdFeB-type ternary nanocomposites usually exhibit a ${}_iH_c$ of less than 9 kOe, regardless of the method of fabrication or elemental substitution/addition. Although the exchange coupled α-Fe/$Nd_2Fe_{14}B$-type nanocomposites of $Nd_8Fe_{87}B_5$ and $Nd_8Fe_{87.5}B_{4.5}$ have been reported to exhibit extremely high B_r (12.5 kG) and $(BH)_{max}$ (23.3 MGOe) [7], the low ${}_iH_c$ (5.3 kOe) may still limit their applications in certain areas; such as micro motors.

Compositions of the present invention can be of the formula: $(RE_{1-y}La_y)_vFe_{100-v-w-x-z}Co_wM_zB_x$, where RE is at least one rare earth element excluding La; M is at least one refractory metal selected from Ti, Zr, Hf, V, Nb, Ta, Cr, Mo and W; v is from about 5 to about 15; w is greater than or equal to 5; x is from about 9 to about 30; y is from about 0.05 to about 0.5; and z is from about 0.1 to about 5.

Suitable rare earth elements include La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu. The total rare earth content of the present compositions is referred to herein as "TRE". The term "RE" as used herein means all of the suitable rare earth elements except La. Preferred RE elements are Nd, Pr,

Dy, Tb and mixtures thereof, with Nd, Pr and mixtures thereof being most preferred. Suitable refractory metals include elements of Groups IVb, Vb, and VIb of the Periodic Table, e.g., Ti, Zr, Hf, V, NB, Ta, Cr, Mo and W. The refractory metal content of the present compositions is referred to herein as "M". Preferably, M is at least one refractory metal selected from Ti, V, Nb, Cr and Mo. More preferably M is at least one refractory metal selected from Ti, Nb and Cr. Most preferably M is Cr or Ti or a combination thereof. The benefits of Cobalt addition to the present nanocomposite material generally begins at about 1% to about 40%. Although the particularly preferred compositions of the present invention comprise equal to or greater than about 5% Co. Typical, preferred and more preferred ranges of TRE, B, M and Co are set forth in the following table:

approximate ranges for:	TRE from about to about:	B from about to about:	M from about to about	Co from about to about	Fe from about to about
typical	5-15	9-30	0.1-5	5-40	balance
preferred	9-12	9-12	0.5-4	5-20	balance
more preferred	9.5-11.5	10-12	0.5-3	6-15	balance
most preferred	9.5-11.5	10.5-11.5	1-2.5	7-12	balance

The magnetic materials of the present invention are preferably produced by a rapid solidification and thermal treatment process. Rapid solidification is achieved by quickly cooling the composition from the molten state by techniques such as melt spinning, jet casting, melt extraction, atomization and splat cooling. Cooling rates of from about 10^4 to about 10^7 °C per second are typically employed, preferably from about 10^5 to about 10^6 °C per second. The rapidly solidified material is preferably substantially amorphous. After rapid solidification the material may be ground, may be ground and heat treated or may be directly heat treated.

The compositions of the present invention have been found to possess improved processibility, allowing slower rapid solidification rates to be used. For example, during the melt spinning process, slower rotational wheel speeds may be used and/or larger volumes of material may be processed. The ability to use slower melt spinning wheel speeds is important because the molten alloy puddle that is in contact with the spinning wheel is substantially more stable when the wheel speed is reduced. Furthermore, the ability to process larger volumes of material allows for reductions in production costs.

After the composition has been rapidly solidified to the substantially amorphous state, it is preferably thermally treated to induce spontaneous crystallization. As used herein, the term "spontaneous crystallization" means the rapid and substantially homogenous formation of fine crystal grains. Spontaneous crystallization is preferably achieved by heating the material to a specified temperature for a controlled period of time, which results in nucleation of crystal grains without substantial subsequent grain growth. Temperatures of from about 400 to about 800°C are suitable, preferably from about 600 to about 750°C, more preferably from about 645 to about 700°C and most preferably from about 645 to about 655°C. Heating times of from about 0.001 second to about 2 hours are preferred, more preferably from about 0.01 second to about 15 minutes and most preferred from about 8 to about 11 minutes. The material may be heated in any suitable apparatus such as a furnace. Continuous and/or batch heating methods may be employed. Preferably, the material is heated to its crystallization temperature and the heat source is removed before substantial grain growth occurs.

Powdered forms of the nanocomposite magnetic materials of the present invention are suitable for use in forming bonded magnets having good magnetic properties. Any conventional method for preparing the bonded magnet can be utilized. Preferably, the powdered nanocomposited magnetic materials are mixed with a binder and cured. The binder preferably comprises from about 0.5 to about 4 weight percent of the bonded magnet.

It has been discovered that the addition of the nanocomposite provides for

materials where the (magnitude of) irreversible loss of induction is less than about -4%, preferably less than about -3.5%, when heated to about 180°C and held for about 15 minutes.

EXPERIMENTAL

The following examples illustrate various aspects of the present invention and are not intended to limit the scope thereof.

Table I: The B_r, $_iH_c$ and $(BH)_{max}$ of the $(Nd_{0.95}La_{0.05})_{9.5}Fe_{78}Cr_2B_{10.5}$ ribbons in the as-spun and after 650, 675 and 700 °C-10 min. thermal treatment.

Ribbon Condition	B_r (kG)	$_iH_c$ (kOe)	$(BH)_{max}$ (MGOe)
as-spun (25m/sec)	7.6	9.9	8.5
650 °C - 10 min.	8.4	10.3	14.0
675 °C - 10 min.	8.2	9.8	12.5
700 °C - 10 min.	8.2	9.5	12.8

Table II. Comparison of B_r, $_iH_c$ and $(BH)_{max}$ of the $(Nd_{0.95}La_{0.05})_{9.5}Fe_{78-x}Co_xCr_2B_{10.5}$ (x=0-10) ribbons after optimum treatment.

Co Content x =	B_r (kG)	$_iH_c$ (kOe)	$(BH)_{max}$ (MGOe)
0	8.4	10.3	14.0
2.5	8.4	10.2	14.1
5.0	8.5	10.2	14.1
7.5	9.1	10.3	15.8
10	10.4	9.5	19.8

Table III. Comparison of the $_iH_c$, irreversible loss of induction and reversible temperature coefficient of induction (conventionally known as α) of the $(Nd_{0.95}La_{0.05})_{9.5}Fe_{78-x}Co_xCr_2B_{10.5}$ (x=0-10) ribbons after optimum treatment.

Co Content x=	$_iH_c$ (kOe)	Irrv. Loss of Induction (%)	α %/(°C)
0	10.3	-3.5	-0.184
2.5	10.2	-2.7	-0.144
5.0	10.2	-3.0	-0.131
7.5	10.3	-3.2	-0.118
10.0	9.5	-3.4	-0.105
Control (commercial)	9.2	-4.5	-0.105

Alloy ingots with compositions of $(Nd_{0.95}La_{0.05})_{9.5}Fe_{78-x}Co_xCr_2B_{10.5}$ (x=0-10) are prepared by vacuum induction melting. Ingots pieces of approximately 3 grams are crushed into small pieces to accommodate the size of the crucible for melt spinning. A quartz nozzle with an orifice of about 0.7 - 0.8 mm in diameter is used for melt spinning. Ribbons are produced with wheel speeds (Vs) ranging from about 15 to about 25 m/s. X-ray powder diffraction with Cu-Kα radiation is utilized to determine the degree of crystallinity in ribbons. The magnetic phases and the corresponding Curie temperatures (T_c) are determined by a Thermal Gravimetric Analyzer (TGA) in conjunction with an externally applied magnet field of 50 Oe, conventionally known as Thermo Magnetic Analysis (TMA). Selected partially amorphous ribbons are thermally treated at from about 650 to about 700°C for about 10 minutes to cause crystallization and to improve the magnetic properties. The as-quenched and the thermally treated ribbons are magnetized with a pulse field of about 50 kOe, and the magnetic properties of the ribbons are measured by a Vibrating Sample Magnetometer (VSM) with an applied

magnetic field of 12 kOe. The open circuit properties, namely, the irreversible loss of induction are determined by placing a fully magnetized ribbon with a size of about 4 mm x 2.5 mm x 50 mm in the VSM under zero applied magnetic field, cycled from about 2 to about 180°C. Wohlfarth's remanence analysis [8,9] is employed to determine the impact of partial Co-substitution for Fe on the strength of exchange-coupled interactions of the materials obtained.

Shown in Fig. 1 are the B_r, ${}_iH_c$ and $(BH)_{max}$ of the $(Nd_{0.95}La_{0.05})_{9.5}Fe_{78}Cr_2B_{10.5}$ ribbons in the as-melt spun state (V_s=25 m/s) and after an isothermal treatment at about 650, 675 and 700°C for about 10 minutes, respectively. For convenience, the B_r, ${}_iH_c$ and $(BH)_{max}$ of these samples are listed in Table I for reference. The B_r, ${}_iH_c$ and $(BH)_{max}$ of the as-spun ribbons, without any thermal treatment, are relatively low: 7.6 kG, 9.9 kOe and 8.5 MGOe, respectively, and can be ascribed to the incomplete crystallization of ribbons, as evidenced by the superposition of broad peaks of amorphous precursor alloy and the characteristics of 2:14:1 and α-Fe peaks shown in Fig 2. After an appropriate annealing, both B_r and $(BH)_{max}$, are improved significantly. A B_r of 8.4 kG, ${}_iH_c$ of 10.3 kOe and $(BH)_{max}$ of 14 MGOe are obtained after a 650°C-10 min. thermal treatment. When treated at higher temperatures, namely about 675 or about 700°C, drastic decreases in B_r and $(BH)_{max}$ can be observed indicating subtle grain growth or phase transformations may have occurred. Unlike B_r or $(BH)_{max}$, the ${}_iH_c$ remains relatively constant at 9.5 to 9.9 kOe after any of the thermal treatments. All values suggest that about 650 °C for about 10 minute treatment can be the preferred thermal treatment for the materials of the present invention.

Shown in Fig. 3 are the variation of optimum B_r, ${}_iH_c$ and $(BH)_{max}$, for the thermal treatments, with the Co content in $(Nd_{0.95}La_{0.05})_{9.5}Fe_{78.5-x}Co_xCr_2B_{10.5}$ alloy series. Initially, both B_r and $(BH)_{max}$ remain almost constant at low Co concentration, i.e., x=2.5 and 5, then increase when x is increased above 7.5. A B_r and $(BH)_{max}$ of more than 9.1 kG and 15.8 MGOe are obtained on samples with x of 7.5 and 10. Such high B_r values suggest the existence of substantial exchange coupling interaction between the magnetically hard and soft phases. Substituting Co for Fe does not appear to impact the ${}_iH_c$ substantially. The ${}_iH_c$ ranges from 9.5

to 10.3 kOe within the compositions of the experiments. A B_r of 10.4 kG, $_iH_c$ of 9.5 kOe and $(BH)_{max}$ of 19.8 MGOe are achieved in ribbons with x=10. The high $_iH_c$ is contrary to the expectation that Co substitution for Fe may weaken the anisotropy constant of the hard magnetic phase and subsequently lead to a decrease in the $_iH_c$ obtained on nanocomposites. Microstructural changes of high Co-content alloy may play a critical role in explaining the high $_iH_c$ values preserved. It is theorized that the Co addition, with the presence of Cr, may change the liquid characteristics of precursor alloy for melt spinning, modify the microstructure of nanocomposites. For convenience, the B_r, $_iH_c$ and $(BH)_{max}$ of this alloy series are listed in Table II for comparison. Shown in Fig. 4 are the second quadrant demagnetization curves of $(Nd_{0.95}La_{0.05})_{9.5}Fe_{78-x}Co_xCr_2B_{10.5}$ (x=0-10) ribbons. The $_iH_c$ and squareness of the demagnetization curves appear insensitive to the amount of Co-substitution. One may theorize that the variation of $(BH)_{max}$ with Co content follows the same trend as B_r.

In order to understand the mechanism causing the changes of B_r and $(BH)_{max}$ with the amount of Co-substitution, the magnetic phase transformation are examined as a result of the Co-content for temperature ranges of from about 25 to about 900°C. Shown in Figs. 5(a), (b), (c), (d) and (e) are the TMA scans of the optimally treated $(Nd_{0.95}La_{0.05})_{9.5}Fe_{78-x}Co_xCr_2B_{10.5}$ ribbons, where x =0, 2.5, 5.0, 7.5 and 10, respectively. Only two magnetic phases, namely, $R_2Fe_{14}B$ and α-Fe, are found in the control sample (x=0). The T_c of 2:14:1 phase is found to increase from about 289 to about 393°C when the Co content is increased from x = 0 to 10. This suggests that Co may, presumably, enter the crystal structure of the $Nd_2(Fe,Co)_{14}B$ phase. The T_c of α-Fe is also found to increase from about 712 to about 860°C when the x is increased from 0 to 10. Again, this change in T_c also implies that Co may also form a solid solution of α-(Fe,Co).

The average grain size of optimally treated ribbons are also compared by x-ray diffraction (XRD) and transmission electron microscopy (TEM). Shown in Figs. 6(a), (b), (c), (d) and (e) are the XRD patterns of the experimental ribbons. Similar peak width of all samples studied indicate that the average grain size of these samples are approximately the same for both α-(Fe,Co) and 2:14:1 phases.

Shown in Figs 7(a), (b) and (c) are TEM analysis of $(Nd_{0.95}La_{0.05})_{9.5}Fe_{78-x}Co_xCr_2B_{10.5}$ with x=0, 5 and 10, respectively. Somewhat more grain growth occurred in the 5% Co-containing alloy (see Figs 7(a) and (b)). The difference in the average grain size becomes less pronounced when the x is increased from 5 to 10 as shown in Figs. 7(b) and (c). It appears, however, that the grain boundary becomes less defined and even surrounded by a smudged secondary phase (not identified) when x is increased to 10. This change in microstructure may explain why the ${}_iH_c$ is insensitive to the Co-content.

Shown in Fig. 8 are plots of δM $(=m_d(H)-(1-2m_r(H))$, where m_d is the reduced magnetization and m_r is the reduced remanence [8,9], with respect to the applied magnetic field of the $(Nd_{0.95}La_{0.05})_{9.5}Fe_{78-x}Co_xCr_2B_{10.5}$ (x=0, 2.5, 5, 7.5 and 10) ribbons of five compositions studied.. The positive δM peak height in these plots indicates the existence of exchange-coupling interaction between magnetically hard and soft phases. Combining the high B_r found in x=7.5 and 10, the grain coarsening phenomenon and change in microstructure, one may conclude that the increase in B_r and $(BH)_{max}$ of these two samples may arise from the increase in the saturation magnetization of both α-(Fe,Co) and 2:14:1 phases because of the Co substitution. Furthermore, this may also suggest that one needs to compromise the exchange coupling interaction, which is enhanced by fine average grains, with the grain coarsening and changes in the microstructure to achieve the highest B_r and $(BH)_{max}$ on high Co concentration materials ($5 < x < 10$). As previously mentioned, Co substitution for Fe increases the T_c of the 2:14:1 phase which may also be attractive for high operational temperature applications.

Shown in Table III are the variation of the ${}_iH_c$, irreversible loss of induction and reversible temperature coefficients of induction, α, with Co concentration of the materials studied. For x=0, the irreversible loss and α are -3.5% and -0.184 %/°C, respectively. Co-substitution for Fe reduces α from -0.184 %/°C to -0.105 %/°C when x was varied from 0 to 10. The decrease in the magnitude of α may be directly related to the increase of T_c as observed in sintered Nd(Fe,Co)B magnets [10]. However, the irreversible loss seems to vary from -2.7 to 3.5% without a correlation to the Co-content within the compositions. For x=10, an irreversible

loss of -3.4% and an α of -0.105%/°C are obtained. These values are comparable to commercially available NdFeB powders (an irreversible loss of -4.5% and α of -0.105 %/°C) for the bonded magnet application.

Only two magnetic phases, i.e., α-Fe and $R_2Fe_{14}B$, are present in the optimally treated magnetic materials of the present invention, including the preferred $(Nd_{0.95}La_{0.05})_{9.5}Fe_{78-x}Co_xCr_2B_{10.5}$ (x=0-10) ribbons. Co-substitution for Fe, i.e. (for example the preferred range of x =2.5 through 10), increases the Curie temperature (T_c) of both α-(Fe,Co) and $R_2(Fe,Co)_{14}B$ phases. The B_r and $(BH)_{max}$ are also increased in samples with high Co-content. Exchange-coupling between the magnetically hard and soft phases can be observed. Grain coarsening is found in optimally processed ribbons with a dilute Co substitution (x = 2.5 and 5) by TEM analysis. The grain coarsening becomes less apparent when x is increased to 6 or higher. At x=10 for example, a smudged grain boundary phase (not identified) surrounding the main phases is observed. A B_r of 10.4 kG, $_iH_c$ of 9.5 kOe and $(BH)_{max}$ of 19.8 MGOe are obtained on preferred compositions such as of the formula: $(Nd_{0.95}La_{0.05})_{9.5}Fe_{68}Co_{10}Cr_2B_{10.5}$. Moreover, the magnitude of the reversible temperature coefficient of induction of fully processed materials are found to decrease with increasing Co-content.

In summary, the phase transformations and magnetic properties of melt spun nanocomposites, e.g., $(Nd_{0.95}La_{0.05})_{9.5}Fe_{78-x}Co_xCr_2B_{10.5}$ (x=0-10), demonstrate two magnetic phases, i.e. α-(Fe,Co) and $R_2(Fe,Co)_{14}B$. Co substitution for Fe, e.g. x=2.5 through 10, increases the Curie temperature (T_c) of both the α-(Fe,Co) and $R_2(Fe,Co)_{14}B$ phases at a rate of approximately 20 °C per % of Co substitution. Minor grain coarsening can be observed on optimally processed ribbons containing low Co-content (e.g., x=5). Further increases in Co-content have no effect on the average grain size obtained. Instead, an unknown grain boundary phase surrounds the main phase on ribbons with x =10 for example. This change in microstructure may be one reason that the $_iH_c$ is preserved at more than 9.5 kOe with increasing Co-content. Exchange-coupling between the magnetically hard and soft phases is found in all samples. The remanence, B_r and maximum energy product, $(BH)_{max}$, are improved drastically at x=7.5 and 10, which may arise from the increases in the

saturation magnetization of α-(Fe, Co) and $R_2(Fe, Co)_{14}B$ as well as the exchange-coupling between them. A B_r of 10.4 kG, ${}_iH_c$ of 9.5 kOe and $(BH)_{max}$ of 19.5 MGOe is achieved in $(Nd_{0.95}La_{0.05})_{9.5}Fe_{68}Co_{10}Cr_2B_{10.5}$. Moreover, the reversible temperature coefficient of induction (conventionally referred to as α) of optimally processed materials is found to decrease with increasing Co concentration.

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What is claimed is:

1. A nanocomposite magnetic material of the formula: $(RE_{1-y}La_y)_vFe_{100-v-w-x-z}Co_wM_zB_x$, where RE is at least one rare earth element selected from the group consisting of Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu; M is at least one refractory metal selected from Ti, Zr, Hf, V, Nb, Ta, Cr, Mo and W; v is from about 5 to about 15; w is greater than or equal to 5; x is from about 9 to about 30; y is from about 0.05 to about 0.5; and z is from about 0.1 to about 5.

2. The nanocomposite material of Claim 1, wherein w is greater than or equal to 6.

3. The nanocomposite material of Claim 1, wherein RE is at least one element selected from the group consisting of Nd, Pr, Dy and Tb.

4. The nanocomposite material of Claim 1, wherein RE is at least one element selected from the group consisting of Nd and Pr.

5. The nanocomposite material of Claim 3, wherein M is at least one refractory metal selected from the group consisting of Ti, V, Nb, Cr, and Mo; v is form about 9 to about 12; w is form about 6 to about 20; x is from about 9 to about 12; y is from about 0.05 to about 0.1 ; and z is from about 0.5 to about 4.

6. The nanocomposite material of Claim 3, wherein M is at least one refractory metal selected from the group consisting of Ti, Nb, and Cr; v is from about 9.5 to about 11.5; w is from about 6 to about 15; x is from about 10 to about 12; y is from about 0.05 to about 0.07; and z is from about 0.5 to about 3.

7. The nanocomposite material of Claim 3, wherein M is Cr; v is from about 9.5 to about 11.5; w is from about 7 to about 12; x is from about 10.5 to about 11.5; y is from about 0.05 to about 0.07; and z is from about 1 to about 2.5.

8. The nanocomposite material of Claim 3, wherein M is Ti; v is from about 9.5 to about 11.5; w is from about 7 to about 12; x is from about 10.5 to about 11.5; y is from about 0.05 to about 0.07; and z is from about 1 to about 2.5.

9. The nanocomposite material of Claim 3, wherein x is greater than or equal to about 9.5.

10. The nanocomposite material of Claim 3, wherein x is greater than or equal to about 10.

11. The nanocomposite material of Claim 3, wherein x is greater than or equal to about 10.5.

12. The nanocomposite material of Claim 3, wherein x is from about 10.5 to about 30.

13. A bonded magnet comprising: a nanocomposite material of the formula: $(RE_{1-y}La_y)_vFe_{100-v-w-x-z}Co_wM_zB_x$, where RE is at least one rare earth element selected from the group consisting of Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu; M is at least one refractory metal selected from Ti, Zr, Hf, V, Nb, Ta, Cr, Mo and W; v is from about 5 to about 15; w is greater than or equal to 5; x is from about 9 to about 30; y is from about 0.05 to about 0.5; and z is from about 0.1 to about 5; and a binder.

14. The bonded magnet of Claim 13, wherein the binder comprises from about 0.5 to about 4 weight percent of the bonded magnet.

15. A method of making a bonded magnet comprising: providing a powdered nanocomposite magnetic material of the formula: $(RE_{1-y}La_y)_vFe_{100-v-w-x-z}Co_wM_zB_x$, where RE is at least one rare earth element selected from the group consisting of Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu; M is at least one refractory metal selected from Ti, Zr, Hf, V, Nb, Ta, Cr, Mo and W; v is from about 5 to about 15; w is greater than or equal to 5; x is from about 9 to about 30; y is from about 0.05 to about 0.5; and z is from about 0.1 to about 5; and mixing the powdered nanocomposite magnetic material with a binder; and curing the binder to form the bonded magnet.

16. The nanocomposite material according to Claim 1, wherein the magnitude of irreversible loss of induction is less than -4% when heated to 180°C for about 15 minutes.

FIG. 1

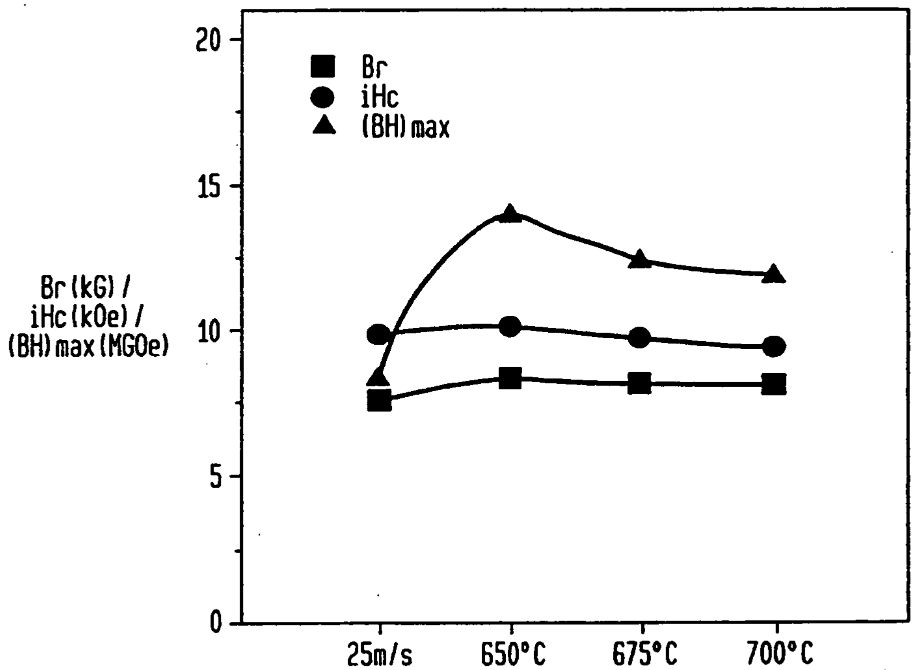

Br
iHc
(BH) max
Br (kG) /
iHc (kOe) /
(BH) max (MGOe)
20
15
10
5
0
25m/s
650°C
675°C
700°C

FIG. 3

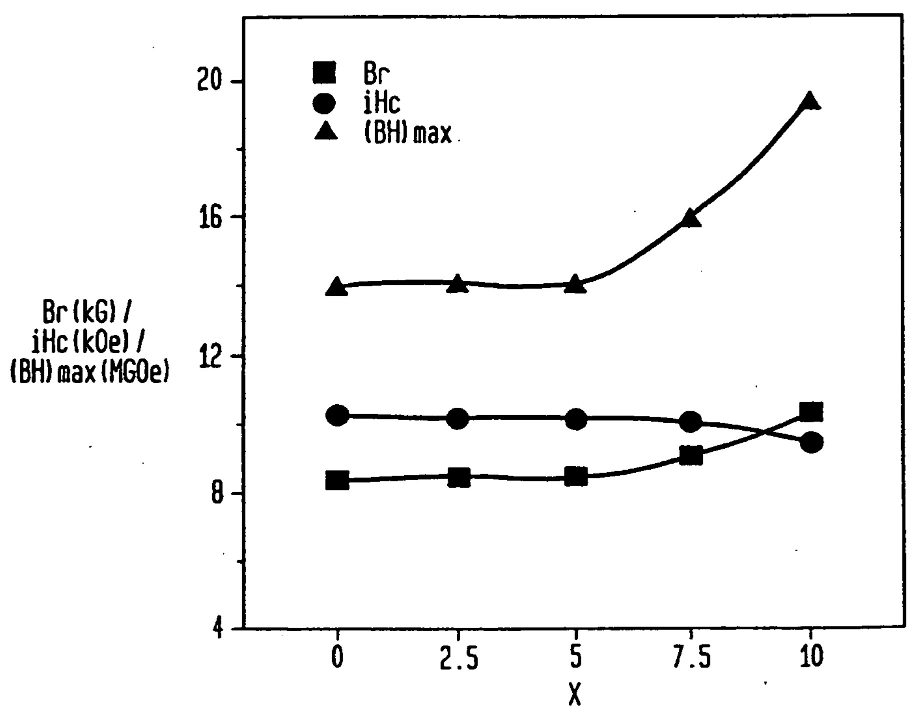

Br
iHc
(BH) max
Br (kG) /
iHc (kOe) /
(BH) max (MGOe)
20
16
12
8
4
0
2.5
5
7.5
10
X

FIG. 2

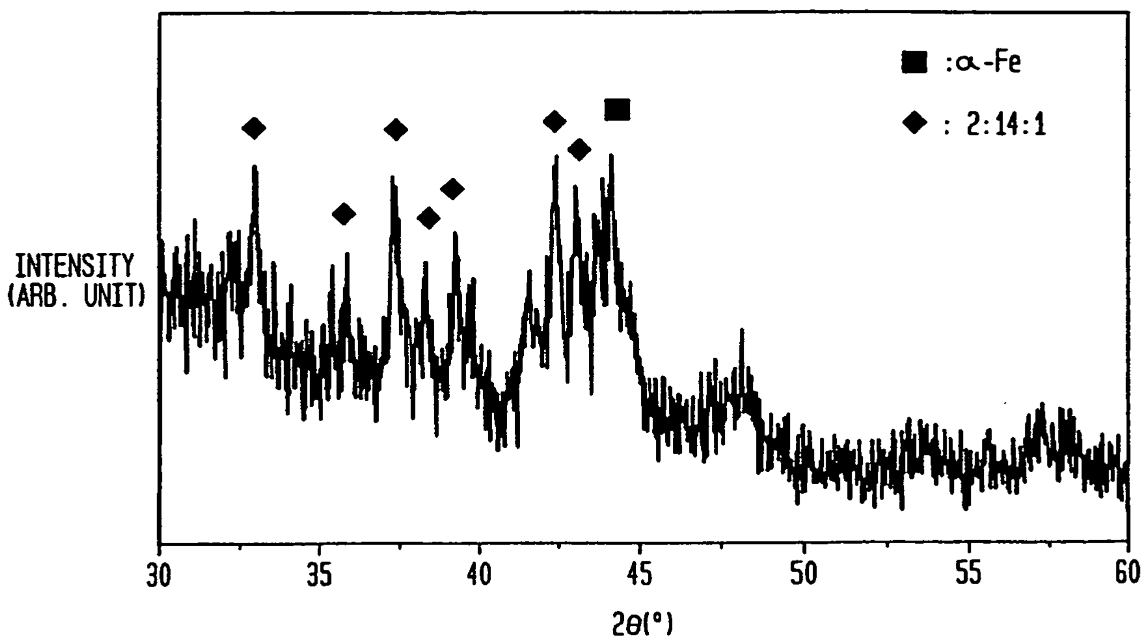

■ :α-Fe
◆ : 2:14:1
INTENSITY (ARB. UNIT)
30
35
40
45
50
55
60
2θ(°)

FIG. 4

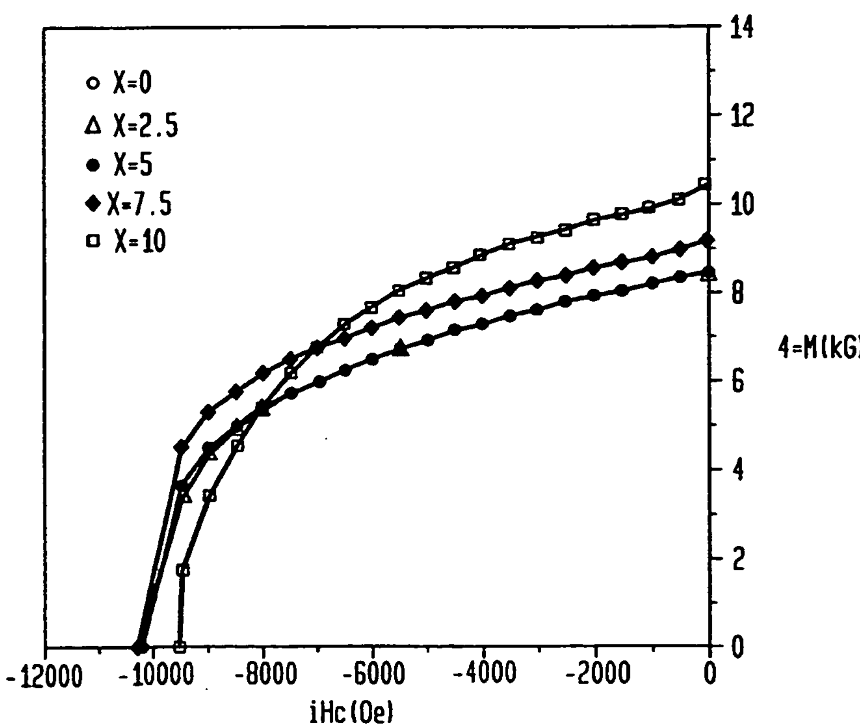

○ X=0
△ X=2.5
● X=5
◆ X=7.5
□ X=10
14
12
10
8
6
4
2
0
4=M(kG)
-12000
-10000
-8000
-6000
-4000
-2000
0
iHc(Oe)

FIG. 5

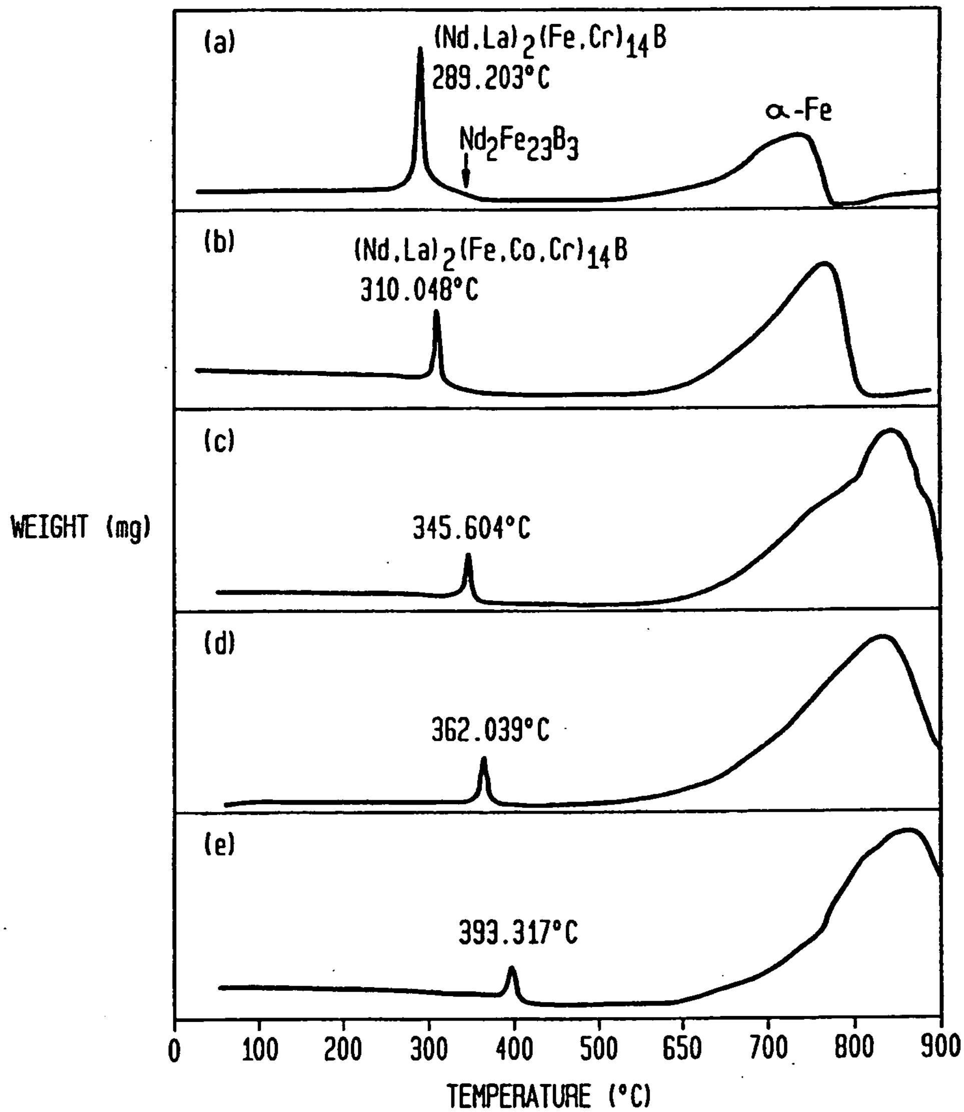

(a)
$(Nd,La)_2(Fe,Cr)_{14}B$
289.203°C
$Nd_2Fe_{23}B_3$
α-Fe
(b)
$(Nd,La)_2(Fe,Co,Cr)_{14}B$
310.048°C
(c)
345.604°C
(d)
362.039°C
(e)
393.317°C
WEIGHT (mg)
0
100
200
300
400
500
650
700
800
900
TEMPERATURE (°C)

FIG. 6

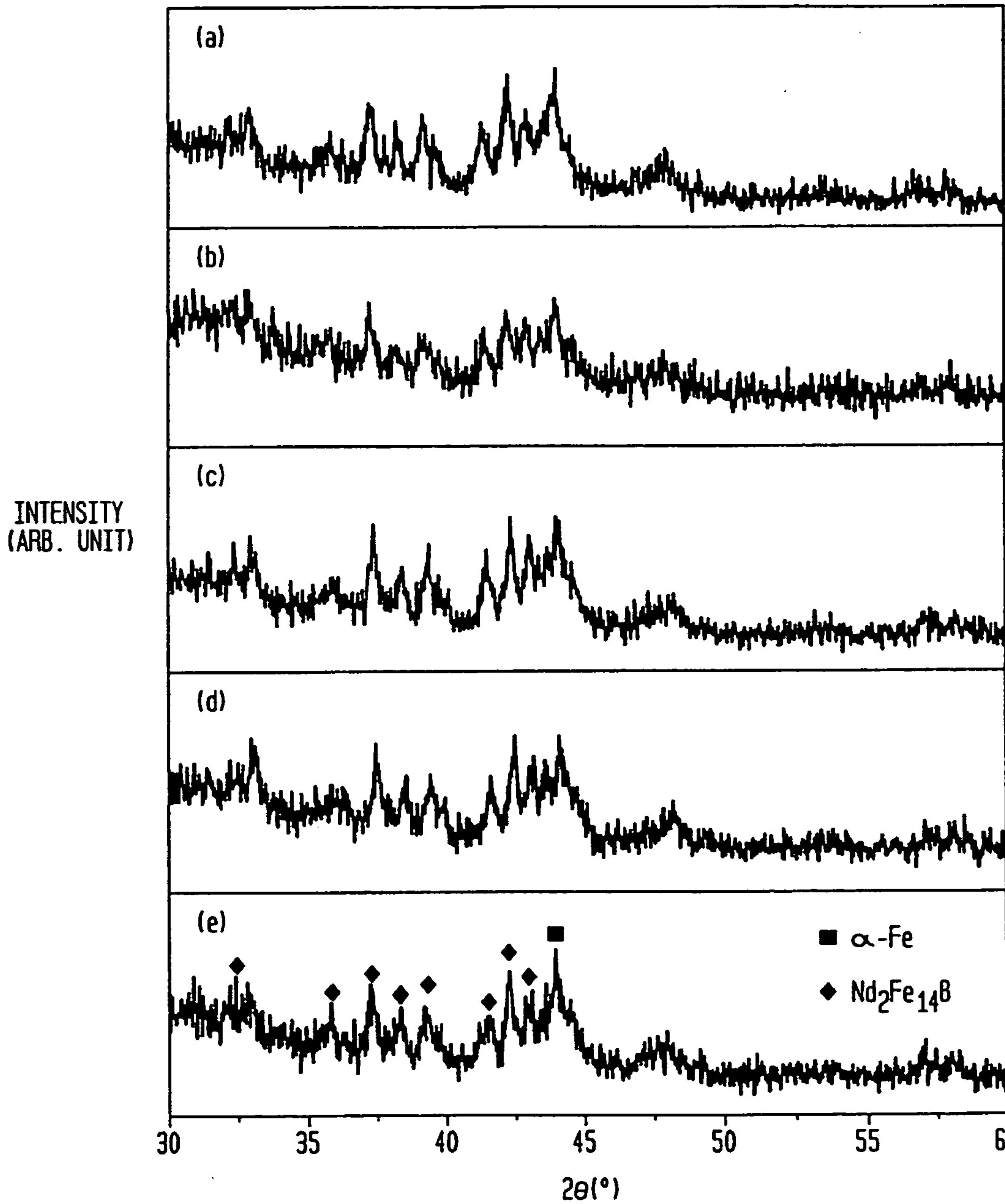


FIG. 7A

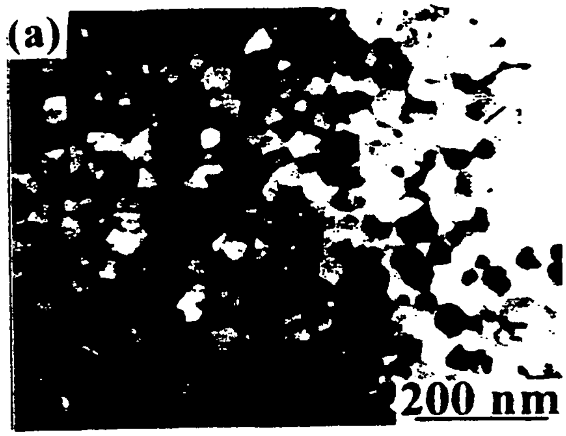


FIG. 7B

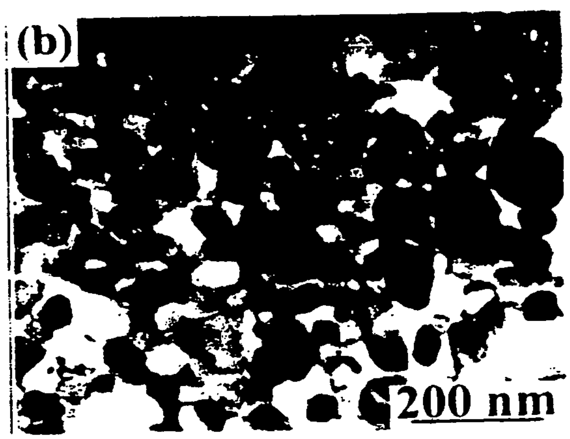
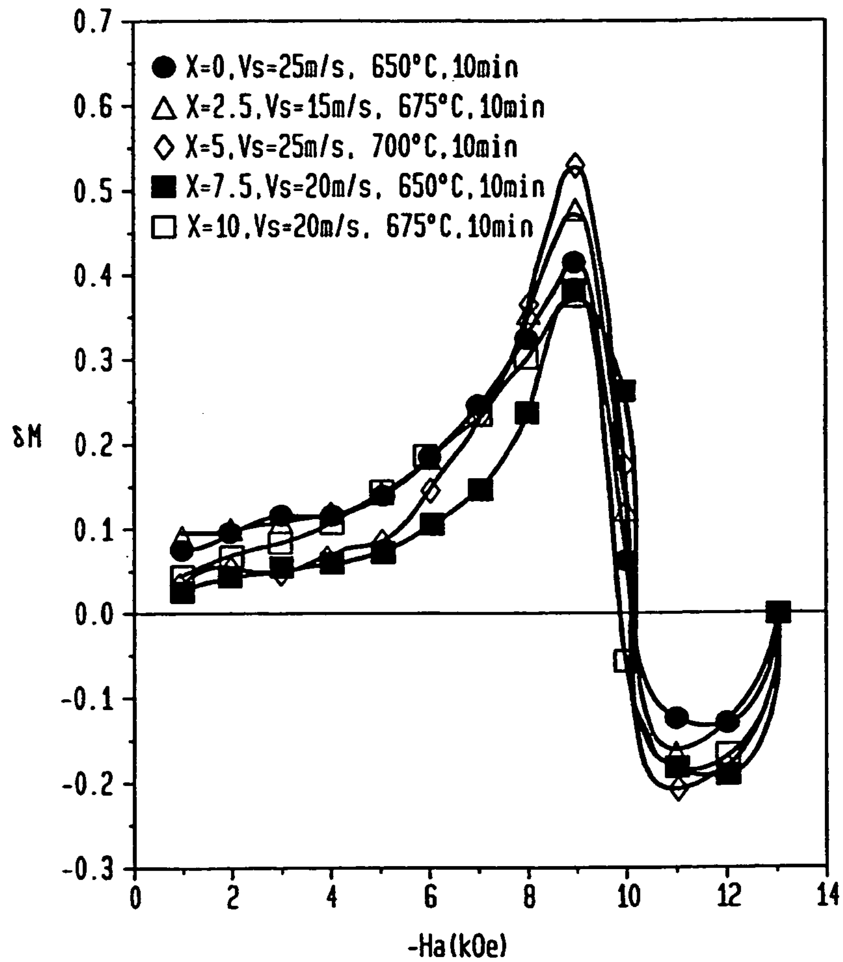


FIG. 7C

FIG. 8


X=0, Vs=25m/s, 650°C, 10min
X=2.5, Vs=15m/s, 675°C, 10min
X=5, Vs=25m/s, 700°C, 10min
X=7.5, Vs=20m/s, 650°C, 10min
X=10, Vs=20m/s, 675°C, 10min
δM
-Ha (kOe)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
0
2
4
6
8
10
12
14

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US99/15439

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :HO1F 1/057, 1/03, 1/26; CO4B 35/04, 35/64; B22F 3/00
US CL :148/302, 104; 252/62.54, 62.55; 420/83, 121
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 148/302, 104; 252/62.54, 62.55; 420/83, 121

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS-USPAT, search terms: rare earth, boron, cobalt, Ti, Zr, Hf, V, Nb, Ta, Cr, Mo, W, La, bond, bind

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y,P	US 5,800,728 A (IWATA) 01 September 1998, column 2, lines 1-22.	1-16
Y	US 5,449,417 A (SHIMIZU et al.) 12 September 1995, column 4, line 42-column 5, line 2.	1-16
Y	US 5,049,208 A (YAJIMA et al.) 17 September 1991, column 4, lines 9-48and column 8, line 56-column 9, line 22 and column 9, lines 37-66.	1-16
Y	US 5,022,939 A (YAJIMA et al.) 11 June 1991, column column 3, line 66-column 4, line 53 column 9, line 63-column 10, line 42.	1-16
Y	US 4,836,868 A (YAJIMA et al.) 06 June 1989, column 3, line 1-column 4, line 19.	1-16

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

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Date of the actual completion of the international search

05 OCTOBER 1999

Date of mailing of the international search report

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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,250,206 A (NAKAYAMA et al.) 05 October 1993, column 3, line 1-29.	1-16
Y	US 4,765,848 A (MOHRI et al.) 23 August 1988, column 3, lines 30-43 and column 6, lines 3-16.	1-16